

OPTIMAL RF SYSTEMS FOR LIGHTLY LOADED SUPERCONDUCTING STRUCTURES

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Abstract

Recent developments in the field of RF accelerators have created a demand for power amplifiers that can support very high accelerating gradients, 15-25 MV/m, in superconducting structures with extremely low losses. Free electron lasers with modest beam current, $I < 10$ uA, or those based on energy recovery linacs may have intrinsic power demands of less than 1 kW/m. We present a design concept for an amplifier and external tuner system that will efficiently meet this requirement. A likely amplifier for this application is the Inductive Output Tube (IOT) which offers high AC/RF efficiency, flexible power output and switching capability without the need for external modulation. The use of solid state amplifiers is also considered. The external tuner circuit makes use of low loss RF components, include waveguide, circulators and ferrite phase shifters to create a moderate quality standing wave between the amplifier and the superconducting cavity. The potential effective Q_{ext} exceeds 3×10^7 . Plans for future work are presented.

INTRODUCTION

For emerging high gradient, low beam power superconducting (SC) accelerators, including energy recovery linacs (ERL's) and free electron lasers (FEL's), the bulk of the generated RF power is reflected from the SC structure and absorbed in an external load, connected to the reflected-power port of a ferrite circulator. MIT is pursuing the design of a system that would recycle this reflected RF power while maintaining adequate phase and amplitude control of the accelerating cavities. This will greatly reduce the power needed from the RF amplifier, thus substantially reducing the capital and operating costs associated with these devices.

The intrinsic RF power required by an ERL or an FEL can be quite low. For today's state-of-the-art superconducting structures with unloaded quality factors (Q_0) in excess of 10^{10} [1] the power to maintain the cavity field amplitude is less than 50 W/m at gradients of 25 MV/m. For average beam currents (or imbalanced currents in the case of an ERL) of less than 10 uA, the beam power is limited to 250 W/m at a gradient of 25 MV/m. An ideal RF source coupled to a

one meter cavity would therefore need to supply only 300 W to meet these demands.

Despite these low intrinsic demands, present accelerator designs call for amplifiers with power capabilities in excess of 5 kW/m [2]. This additional power is necessary to compensate for small changes in the superconducting cavity geometry due to mechanical vibrations. This problem, known as microphonics, can be addressed by spoiling the cavity quality factor with a stronger coupling to the amplifier than would be necessary in the absence of the microphonic perturbation.

One strategy under development is to actively correct the cavity geometry by means of a piezo-restrictive tuner [3]. This tuner adjusts the length of the cavity to compensate for the mechanical vibrations and maintain the cavity center frequency. The device must be able to correct the micron scale deformations of the cavity at frequencies between DC and a few hundred Hz.

Another approach is to make use of an external tuner to apply a corrective phase shift to the reflected RF wave and reintroduce it to the cavity structure [4, 5]. In essence a second standing wave circuit of much lower quality factor has been introduced into the RF system between the amplifier and the superconducting structure. The necessary external control (phase shift) could be realized by means of low loss ferrite phase shifters similar to those presently in use at the Bates accelerator. Such phase shifters with very low insertion loss (< 0.7 dB), adequate range ($d\phi > \pm 90^\circ$), resolution ($d\phi < 1^\circ$), and high power handling capability ($P_{\text{avg}} > 5$ kW), are now available commercially. Efforts are also underway at Fermilab National Accelerator Laboratory to construct a device with similar specifications for use in tuning individual cavities of the TESLA Test Facility II Accelerator [6].

INTRINSIC RF POWER DEMAND

The power demand for an RF cavity can be divided into two categories: power to maintain the cavity fields and power to accelerate the beam. Equation 1 shows the distribution of these power requirements:

$$P = \frac{V^2}{(r/Q)Q_{\text{ext}}} \cdot \frac{\beta + 1}{4\beta} \cdot \left[(1 + a + b)^2 + (2Q_{\text{ext}} \frac{\delta\omega}{\omega})^2 \right] \quad (1)$$

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Here P is the power required by the RF amplifier, V is the cavity peak voltage, r/Q is the cavity shunt impedance, β is the coupling factor, a and b are factors for the beam power at two distinct phases (these terms almost cancel in the case of the ERL) and $\delta\omega$ is a measure of the frequency variation of the cavity due to uncontrolled sources. For superconducting structures where β is much greater than unity and applications with negligible beam loading equation 1 becomes

$$P = \frac{V^2}{4(r/Q)Q_{ext}} \cdot \left[1 + (2Q_{ext} \frac{\delta\omega}{\omega})^2 \right] \quad (2)$$

Note that the power requirement due to the last term in equation 2 pertaining to the frequency variation of the cavity would vanish if the RF source was able to vary its frequency to match the variation in the cavity center frequency. Clearly this is not acceptable for an accelerator where many 100's of individual cavities must be phase locked with respect to each other. In this case additional amplifier power is required to compensate for a lower gain as the cavity frequency fluctuates about the linac center frequency.

In the case where the beam power is small, the width of the frequency variation determines the optimum coupling and thus the power demand of the cavity. Figure 1 shows the power demand at a beam current of 10 uA as a function of coupling factor for several values of the frequency variation width.

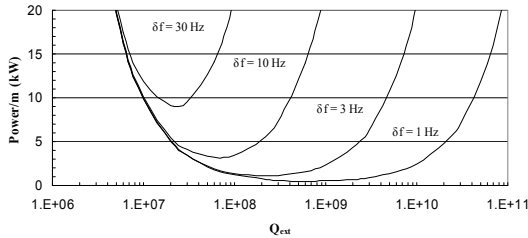


Figure 1: Amplifier power demand vs external coupling (Q_{ext}) for TESLA cavities at 1.3 GHz. All curves assume a cavity voltage of 25 MV and a beam current of 10 uA.

Notice that if the frequency variation could be controlled at the level of 1 Hz the required power would be reduced to less than one kW per RF amplifier. The use of solid-state amplifiers rather than vacuum tubes might then become possible.

Initial results using a piezo tuner indicate that in some environments microphonics can be controlled to values less than 50 Hz [Hof03]. The piezo tuner also has substantial advantages in that it is a very low power device and it has the potential to maintain the cavity

center frequency by applying a correction directly to the source of the perturbing influence, ie variations in the cavity length. However the piezo also requires operation at cryogenic temperatures and will have limited access inside the cryomodule in the event of a failure. Further, the piezo device has its own mechanical resonances which may interfere with control system performance if the self-resonance frequency overlaps with the microphonic excitation to be controlled.

The approach considered here to reduce the frequency variation of the system is by the introduction of an additional external oscillator of much lower Q . Corrective phase shifts can be applied to the external system which will reduce the frequency variation of the coupled system.

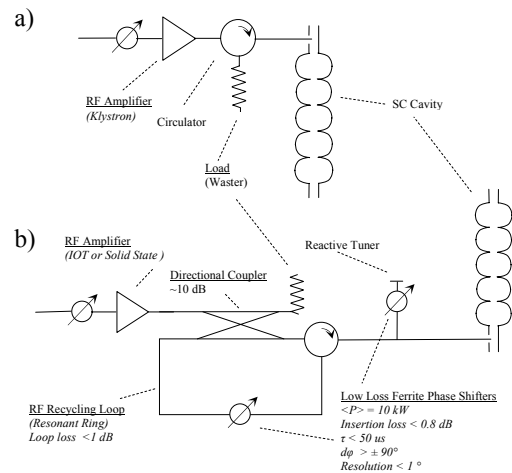


Figure 2: Standard Amplifier Configuration (a) and reactive tuner/RF recycler configuration (b).

Figure 2 shows conceptually how a higher value of Q_{ext} might be reached with the introduction of an external tuner and resonant ring into the amplifier cavity circuit. Figure 2a shows the standard configuration where the amplifier output is delivered to the cavity through a “protected” system, including circulator and load. All reflected power from the cavity is delivered to the load port of the circulator. In Figure 2b several new features have been introduced into the amplifier/tuner circuit. First, the klystron is replaced with either an Inductive Output Tube or Solid State power amplifier. Second, the amplifier is coupled into a resonant ring waveguide structure through a directional coupler of -10 dB. The optimum value of the coupling will depend on the losses in the resonant ring. The phase of the traveling wave in the ring is adjusted by means of a low loss phase shifter which does not

Beam & Cavity Power	Circulator Loss (dB)	Phase Shifter Loss (dB)	Other Loss (dB)	Total Loss (dB)	Dir. Coupler (dB)	Power Gain (G)	P _{ring} (kW)	P _{source} (kW)
240	0.00	0.00	0.00	0.16	14.4	27.3	10	<0.4
240	0.35	0.35	0.14	1.00	6.8	4.8	10	2.1
240	0.45	0.45	0.14	1.20	6.1	4.1	10	2.5
240	0.60	0.60	0.14	1.50	5.3	3.4	10	3.0
240	0.70	0.70	0.14	1.70	4.9	3.0	10	3.4
240	0.80	0.80	0.24	2.00	4.3	2.7	10	3.7

Table 1: Amplifier power requirements and resonant ring power gain for varying component insertion losses. The value of the directional coupler is optimized for each different total loss. 20 MV/m, 10 uA beam current and $Q_{\text{ext}}=10^7$ are assumed

require fast response time for CW beams as it will respond to variations in the real component of the cavity power which should depend only on changes in the dissipated power. Third, a reactive tuner has been installed on the waveguide leg between the resonant ring and the superconducting cavity. This tuner makes use of a low loss ferrite phase shifter as it will require operation at bandwidths significantly greater than the frequency of the microphonic excitation. The enhancement in field strength in the resonant structure should exceed a factor of two and will depend critically on the losses in the phase shifter and circulator. Table 1 list the optimum coupling of the resonant ring as a function of ring losses and indicates that amplifier powers of only ~ 3 kW should be necessary to achieve stable operation at gradients of 20 MV/m.

RF AMPLIFIER SELECTION

At an operating frequency of 1.3 GHz three distinct amplifier types appear to have the potential to meet the power needs of these lightly loaded SRF cavities. They are the klystron, the inductive output tube (IOT) and the solid-state power amplifier (SSPA). As described above the power demand is likely to fall in the range of 2-15 kW per meter of accelerating structure. The exact power requirement will depend on the beam loading and the degree to which the cavity center frequency can be controlled. Both klystron and IOT offer power levels in excess of 10 kW. The klystron is the more established amplifier for accelerator applications, while the IOT technology is presently in the prototype stage at frequencies in the 1-2 GHz range. SSPA's have lower power capability but may offer many system advantages in simplicity, size, cost, flexibility, and reliability and maintenance.

Prototype IOTs have recently become available at frequencies of interest. The EIMAC Division (San Carlos, CA) of CPI has built four devices at 1300 MHz for accelerator applications, which have demonstrated 20 kW power output, 23 dB gain and over 50%

efficiency (more is expected). In addition, THALES has also developed a 1.3 GHz IOT and L3 Corp. (formerly Litton Electron Dynamics) also produce IOTs for UHF TV service and will have a prototype IOT at 1300 MHz in few months.

IOTs are operated near Class B, approaching a conduction angle of 180 degrees, and a maximum theoretical efficiency of 78.5% ($\pi/4$). Practical UHF IOTs have demonstrated efficiency above 70%. Efficiency of an IOT operating at 1300 MHz is less than that of a lower-frequency device because of increased losses in the cavities and distortion of the cathode-current "discs" due to transit-time effects. Nevertheless, computer-simulated data shows conversion efficiency exceeding 68%, which has yet to be demonstrated in the prototypes.

In addition to the advantage of high efficiency the IOT offers a very flexible pulse structure and power output. Unlike the klystron the IOT's efficiency is maintained across a wide dynamic range in power. Further the IOT does not require external modulation. Removal of the low power RF from the IOT grid turns off the beam current in the tube. As the IOT is electrically "short" it has a low phase pushing factor of about one degree per percent relative voltage variation. One drawback of the IOT as compared to the klystron is lower gain. The IOT offers ~ 23 dB where in the case of the klystron gains in excess of 40 dB are readily achieved. This lower power gain of the IOT will place additional demands on the RF driveline distribution system.

Although no SSPA can compete with either a klystron or an IOT at the 15 kW output level, the successful realization of the tuning circuit described above would require amplifier power no greater than ~ 3 kW. A 1.3 GHz SSPA at 3 kW CW is quite practical and has certain advantages, including low-voltage operation and low phase and amplitude pushing factors. At every frequency there is a "cross-over" power level above which the relative advantages of Microwave Vacuum Electron Devices (MVEDs)

exceed those of SSPAs. A power level of 3 kW is probably below the “cross-over” point.

SUMMARY & RESEARCH PLAN

In the past year a team of MIT faculty and accelerator physicists at the Bates laboratory have proposed creating a Center for Accelerator Science and Technology (CAST) at MIT. The core missions of this center would be to educate students in the field of accelerator science and to promote the development of cutting edge accelerator technologies. Under the auspices of CAST MIT Bates has developed a three year plan to design, construct and qualify the highly efficient RF amplifier, RF recycler and reactive tuner system described above. The first phase will be devoted to an analysis of the amplifier performance, component requirements and engineering design. A preliminary model using the MATLAB Simulink platform will be refined. Further measurements of the open and closed loop characteristics of existing cavities at JLAB, TTF and other labs will be performed. These results will be evaluated to produce a set of specifications for the amplifier-tuner system which should yield an effective coupling of $Q_{\text{ext}} > 3 \times 10^7$ while still maintaining adequate phase and amplitude control of the cavity. In the final phase of this effort the system would be assembled at Bates and subsequently tested at one of the laboratories with the appropriate SRF cavity infrastructure

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